

## Two-particle correlations with strange baryons and mesons at RHIC

Jana Bielcikova<sup>1</sup> for the STAR Collaboration

<sup>1</sup> Department of Physics, Yale University, P.O.Box 80124, New Haven, CT-06520, USA

**Abstract.** We present results on two-particle correlations using singly-strange particles ( $\Lambda$ ,  $\bar{\Lambda}$ ,  $K_S^0$ ) and charged hadrons at intermediate  $p_T$  in d+Au and Au+Au collisions at RHIC. We discuss properties of the near-side correlation peak in both azimuthal and pseudo-rapidity space and separate jet-like contributions from the long-range pseudo-rapidity correlations (the ridge). In particular, we study the centrality and  $p_T$  dependence of the jet and ridge yields for various trigger and associated particle species and compare the results to model predictions.

*Keywords:* heavy-ion collisions, strangeness, two-particle correlations, baryon/meson ratio, recombination

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### 1. Introduction

Heavy-ion collisions at relativistic energies provide a unique tool for studies of strongly interacting matter under extreme conditions of high temperature and energy density. Studies of particle production at the top RHIC energy ( $\sqrt{s_{NN}} = 200$  GeV) revealed a strong suppression of inclusive transverse momentum ( $p_T$ ) distributions of identified light hadrons in central Au+Au collisions with respect to p+p, d+Au and peripheral Au+Au collisions [1, 2]. This suppression, commonly referred to as jet quenching, reaches in central Au+Au collisions a value of about 0.2 and is present out to large transverse momenta ( $p_T \approx 12$  GeV/c). This observation is accompanied by enhanced baryon production [3] in the intermediate- $p_T$  range of  $\approx 2$ -6 GeV/c. The measured baryon/meson ratios in both non-strange and strange quark sectors increase with  $p_T$  up to about  $p_T \approx 3$  GeV/c, where the enhancement of baryon/meson production reaches its maximum value of  $\approx 3$  relative to p+p collisions. A fall-off of the baryon/meson ratio is observed for  $p_T > 3$  GeV/c and both,

non-strange and strange baryon/meson ratios, approach each other and eventually reach the values measured in p+p collisions at  $p_T \approx 6$  GeV/c.

These findings suggest that a dominant source of particle production at intermediate  $p_T$  is not from jet fragmentation, rather, parton recombination and coalescence models have been suggested as alternative mechanisms [5, 6, 7, 8]. In these models, competition between recombination and fragmentation results in a shift of the onset of the perturbative regime to higher transverse momenta  $p_T \approx 4$ -6 GeV/c. Due to the steeply falling parton transverse momentum spectrum, the fragmentation process is a much less efficient particle production mechanism than recombination. Moreover, the steeply falling parton spectrum favors recombination of three quarks to form a baryon over the recombination of two quarks to form a meson with the same  $p_T$ . Such mechanisms then naturally lead to an increased production of baryons relative to mesons which is in qualitative agreement with the data.

In addition to the inclusive measurements, studies of two-particle correlations of charged hadrons in Au+Au collisions revealed the presence of additional long-range pseudo-rapidity correlations on the near-side commonly referred to as the *ridge* [9]. Such extended pseudo-rapidity correlations are absent in p+p and d+Au collisions.

It is expected that studies of two-particle azimuthal correlations using identified particles will help to understand processes relevant for particle production at intermediate  $p_T$  and give insight into the origin of the ridge. The wealth of data collected by the STAR experiment at  $\sqrt{s_{NN}} = 200$  GeV offers the possibility of a detailed study of strangeness production up to high  $p_T$ . In this paper, we discuss the properties of two-particle correlations using strange particles ( $\Lambda$ ,  $\bar{\Lambda}$ ,  $K_S^0$ ) as well as unidentified charged particles in d+Au and Au+Au collisions. We focus our discussion on properties of the near-side correlation peak in both azimuthal and pseudo-rapidity space and separate jet-like contributions from the long-range pseudo-rapidity correlations. In particular, we study the centrality and  $p_T$  dependence of the jet and ridge yields for various trigger and associated particle species and compare the results to model predictions.

## 2. STAR experiment

STAR is a large acceptance, multi-purpose spectrometer consisting of several detectors inside a large solenoidal magnet with a magnetic field of 0.5 T. The analysis presented in this paper is based exclusively on charged particle tracks detected and reconstructed in the Time Projection Chamber (TPC). The TPC is well suited for the correlation studies because of its full azimuthal coverage. The TPC provides up to 45 independent spatial and energy loss ( $dE/dx$ ) measurements along each charged particle track. The momentum resolution is determined to be  $\Delta k/k \sim 0.0078 + 0.0098 \cdot p_T$  (GeV/c), where  $k$  is the track curvature proportional to  $1/p_T$ . More details can be found elsewhere [10].

The weakly decaying strange particles (V0s) are reconstructed by a topological

analysis from their decay products measured in the TPC. The geometrical cuts have been optimized to achieve a very clean sample of the V0 particles. Above  $p_T > 2$  GeV/ $c$  the signal to background ratio with these cuts is approximately 15:1.

The results presented in this paper are based on the d+Au data set taken in 2003 and Au+Au data set measured in 2004 at  $\sqrt{s_{NN}} = 200$  GeV.

### 3. Data analysis

In the following paragraphs, we discuss properties of the near-side azimuthal correlations using identified strange particles ( $\Lambda$ ,  $\bar{\Lambda}$ , and  $K_S^0$ ) and unidentified charged particles either as a trigger or an associated particle. The azimuthal distributions among trigger and associated particles in a given centrality bin are defined as:

$$C(\Delta\phi) = \frac{1}{N_{trigger}} \iiint dp_T^{trigger} dp_T^{associated} d(\Delta\eta) \frac{dN_{pair}(p_T^{trigger}, p_T^{associated}, \Delta\phi, \Delta\eta)}{\epsilon(p_T^{associated})}, \quad (1)$$

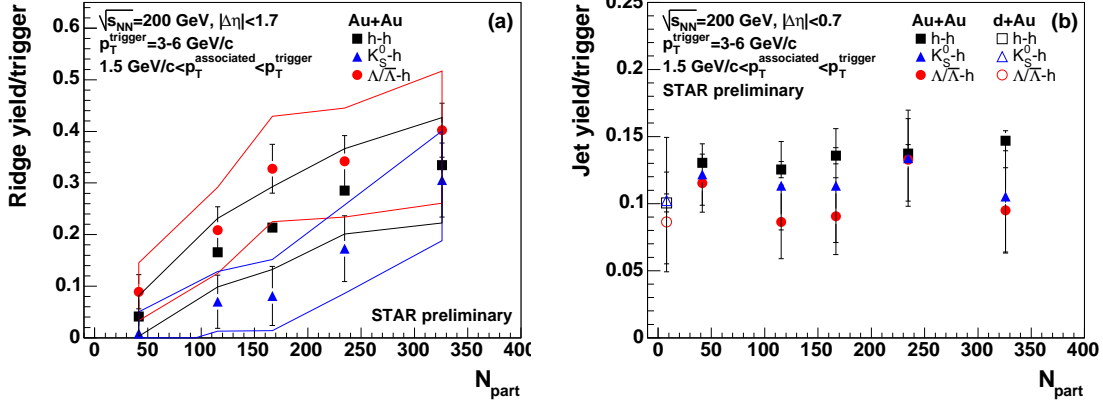
where  $\Delta\phi = \phi^{trigger} - \phi^{associated}$ ,  $N_{trigger}$  is the number of trigger particles, and  $\epsilon$  is the reconstruction efficiency of associated particles. The correlation functions are also corrected for the triangular acceptance in  $\Delta\eta$  and TPC sector boundaries in azimuth.

The data are fit with two Gaussians on top of a flat background in d+Au and elliptic flow ( $v_2$ ) modulated background in Au+Au collisions, respectively. The yield of associated particles is calculated as the area under the Gaussian peak. We study separately the jet and ridge contributions to the near-side yield by analyzing the correlations in two  $\Delta\eta$  windows:  $|\Delta\eta| < 0.7$  containing both jet and ridge correlations, and  $|\Delta\eta| > 0.7$  containing only the ridge contributions, assuming the jet contribution at large  $\Delta\eta$  is negligible. Assuming uniformity of  $v_2$  with  $\eta$ , the jet yield is free of systematic uncertainties due to the elliptic flow subtraction. For the ridge yield, these systematic errors are estimated by subtracting the  $v_2$  measured by the event plane method (the lower bound) and by the 4-particle cumulant method (the upper bound). The uncertainties in the elliptic flow subtraction result in about a 30% systematic error on the extracted associated yield.

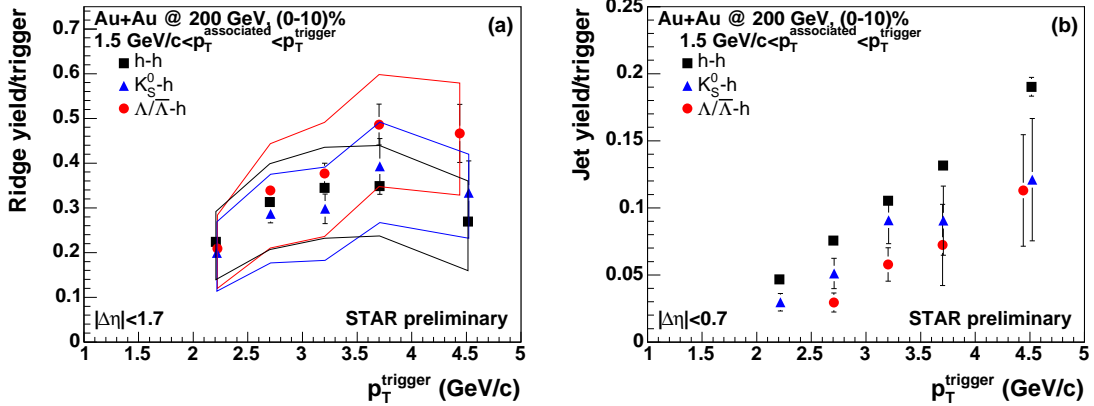
### 4. Results

We first discuss properties of correlations using identified trigger particles which are associated with charged particles. Comparing d+Au and Au+Au collisions, we observe an increase of the near-side yields by a factor of 3-4 going from d+Au to central Au+Au collisions for all studied trigger species. Figure 1 shows separately the centrality dependence of the ridge and jet yields of the near-side correlation. While the jet yield is approximately independent of centrality and consistent with its value in d+Au, the ridge yield increases steeply with centrality.

The observed increase of the near-side yield with centrality is qualitatively in line with the recombination model expectations and points toward a significant



**Fig. 1.** Centrality dependence of the ridge yield (a) and jet yield (b) of associated charged particles for various trigger species in d+Au and Au+Au collisions. The error bands indicate systematic errors on the ridge yield due to the  $v_2$  subtraction.



**Fig. 2.** Dependence of the ridge yield (a) and jet yield (b) on  $p_T^{trigger}$  for various trigger species in central (0-10%) Au+Au collisions. The bands indicate systematic errors on the ridge yield due to the  $v_2$  subtraction.

role of thermal-shower recombination in Au+Au collisions [ 11]. Because the long range pseudo-rapidity correlations play a significant role in Au+Au collisions in the studied  $p_T$  range, a check of how well the individual jet and ridge contributions are

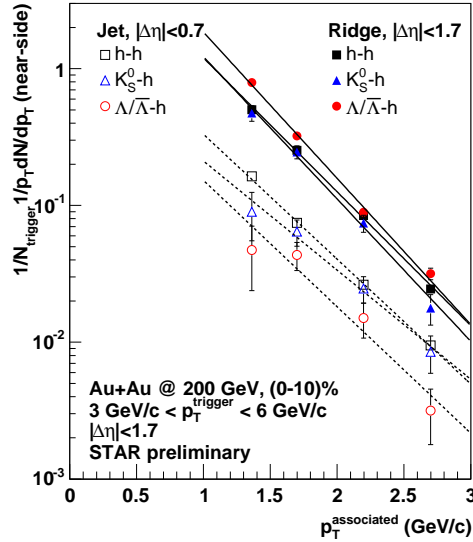
Trigger particle	T(ridge) MeV	T (jet) MeV
$h^\pm$	$438 \pm 4$ (stat.)	$478 \pm 8$
$K_S^0$	$406 \pm 20$ (stat.)	$530 \pm 61$
$\Lambda$	$416 \pm 11$ (stat.)	$445 \pm 49$

**Table 1.** Inverse slope of associated particle spectra for jet and ridge in central Au+Au collisions.

reproduced in the model is required as well. More detailed discussion on possible mechanisms of ridge origin is given in Section 5.

Next, we study the dependence of the jet and ridge yields on the transverse momentum of the trigger particle,  $p_T^{trigger}$ , shown in Figure 2. While the ridge yield increases with  $p_T^{trigger}$  and flattens off for  $p_T^{trigger} > 3$  GeV/c, the jet yield keeps increasing with  $p_T^{trigger}$  as expected for jet-like processes. The jet yield for  $\Lambda$  triggers is systematically below that of charged hadron and  $K_S^0$  triggers. This can be partially attributed to the larger width of the baryon triggered correlations with respect to the meson triggered case. In addition, remaining effects of artificial track merging, which result in the yield loss, affect V0s more than charged tracks. These effects are currently under investigation.

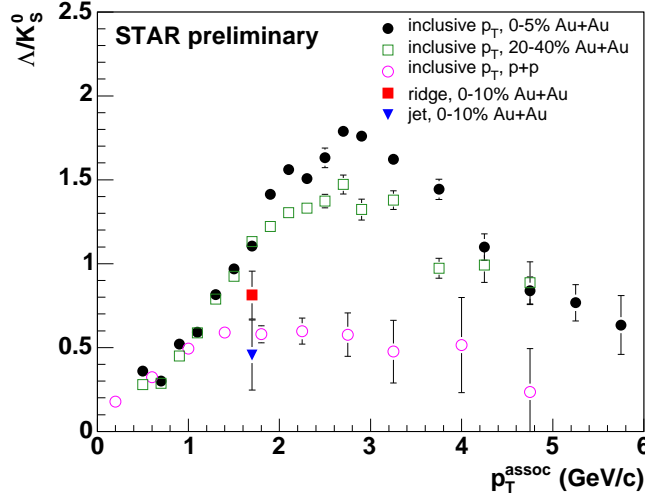
We have also measured the invariant  $p_T$  spectra of associated charged particles for  $p_T^{trigger} = 3$ -6 GeV/c in central Au+Au collisions as shown in Figure 3. We have



**Fig. 3.** Invariant  $p_T$  distribution of associated charged particles in the jet and ridge in central Au+Au collisions for various trigger species indicated by the legend. The curves are exponential fits to the data.

fit the distributions with an exponential function  $e^{-p_T/T}$  and extracted the inverse slope,  $T$ , given in Table 1. The ridge spectra have, averaged over all studied trigger species,  $T = 420 \pm 8$  MeV, close to that of the bulk when the fit is performed in the same  $p_T$  range. The jet spectra have  $T = 480 \pm 30$  MeV. A detailed investigation of the evolution of the inverse slope of the jet and ridge spectra with  $p_T^{trigger}$  has been carried out with charged trigger and associated particles [9], where the statistics are richer than for identified correlations. A clear difference in the evolution of the slope with  $p_T^{trigger}$  was observed for jet and ridge-like correlations. While the inverse slope of the ridge spectra remains constant with increasing  $p_T^{trigger}$  and differs from the bulk by about 50 MeV, the jet spectra show a steep increase of the slope with  $p_T^{trigger}$ .

It is interesting to study the composition of particles in the ridge and jet in order to look for a possible enhancement of the baryon/meson ratio which is present in the inclusive  $p_T$  distributions in Au+Au collisions. We have carried out a preliminary study of two-particle correlations using charged trigger particles with  $p_T^{trigger} = 2$ -3 GeV/c which were associated with identified strange particles with  $1.5 \text{ GeV}/c < p_T^{associated} < p_T^{trigger}$ . Using the same method as above, we have extracted the jet and ridge yields and calculated the  $\Lambda/K_S^0$  ratio. The obtained results on this baryon/meson ratio for particles associated with the jet and ridge are shown in



**Fig. 4.**  $\Lambda/K_S^0$  ratio measured in inclusive  $p_T$  distributions, near-side jet and ridge-like correlation peaks in Au+Au collisions together with this ratio obtained from inclusive  $p_T$  spectra in p+p collisions.

Figure 4 together with the ratio measured from the inclusive  $p_T$  spectra. The  $\Lambda/K_S^0$  ratio calculated for the jet is  $0.46 \pm 0.21$  and consistent with that measured in p+p. The same ratio in the ridge is  $0.81 \pm 0.14$ , higher than in the jet. The large statistical errors do not allow to draw a definite conclusion on the origin of the ridge yet.

## 5. Summary and discussion

We have reported results on the properties of the near-side correlation peak at intermediate- $p_T$  at RHIC using strange particles and unidentified charged hadrons. The measured correlations reveal a strong contribution from the long-range  $\Delta\eta$  correlations at near-side for all studied particle species. The strength of these ridge-like correlations increases steeply with centrality and the inverse slope of the associated particle spectra is, by  $\approx 50$  MeV, higher than that of particles produced in the bulk. More data and studies are needed to draw final conclusions on the baryon/meson ratios in the ridge. The jet yield is, contrary to this, independent within errors of centrality in Au+Au collisions and consistent with that in d+Au collisions. In addition, the baryon/meson composition in the jet in Au+Au is close to that measured in p+p collisions.

While the existence and properties of the jet-like correlations are as those in p+p and d+Au collisions, the origin of the ridge is not fully understood. This phenomenon has triggered significant interest in the theoretical community and several models are currently available to describe the observed ridge. Below we discuss their main features.

A model based on the recombination and fragmentation of partons in the medium [12], links the origin of the ridge to the longitudinal expansion of the thermal partons that are enhanced by the energy loss of a hard parton traversing the medium. The model predicts that the baryon/meson ratio of particles associated with the ridge should follow that of particles produced in the bulk and therefore lead to an increased production of baryons. In addition, the model predicts the inverse slope of the enhanced thermal parton distribution to be only by 15 MeV larger than that of particles in the bulk. The data show that over a broad range of  $p_T^{trigger} = 3-12$  GeV/ $c$ , this difference is  $\approx 50$  MeV.

Another suggested mechanism for the ridge origin is based on jet quenching and strong radial flow [13]. The radial expansion of the system is predicted to create strong position-momentum correlations that lead to characteristic rapidity, azimuthal and  $p_T$  correlations among produced particles.

In another approach, the interaction of high- $p_T$  partons with a dense medium under the presence of strong longitudinal collective flow is predicted to lead to a characteristic breaking of the rotational symmetry of the average jet energy and multiplicity distribution in the  $\eta \times \phi$  plane [14]. This will in turn cause a medium-induced broadening of gluon radiation in pseudo-rapidity and form a ridge in  $\Delta\eta$ .

The effects of momentum broadening of a heavy quark in an anisotropic plasma

have also been studied [15]. It is shown that the momentum broadening, induced by collisional energy loss in the leading logarithmic approximation, is more pronounced along the longitudinal direction than in the reaction plane. Unfortunately, in its current form, this model is not directly applicable to our data. First of all, the ridge has been observed for light hadrons while the calculation is done for heavy quarks only. Secondly, the large value of the momentum space anisotropy parameter required by the calculation to describe the data is incompatible with the low shear viscosity of the medium at RHIC as pointed out elsewhere [16].

The mechanism proposed in [16], relates the origin of the ridge to the longitudinal expansion of the medium and spontaneous formation of extended color fields in such expanding medium due to the presence of plasma instabilities. The predicted ridge at low transverse momenta is expected to decrease with increasing energy of the associated radiation. The momentum range of the partons contained in the ridge is in the recombination regime and therefore the authors of this model predict that it would reflect itself in the baryon to meson ratio of associated hadrons.

In order to draw final conclusions about the origin of the ridge, more quantitative theoretical calculations are needed.

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